FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING

Oskari Rajala
Jere Kinnunen
Mikael Särkiniemi

POTENTIAL OF CONSUMER EEG FOR REAL-TIME INTERACTIONS IN IMMERSIVE VR

Bachelor's Thesis
Degree Programme in Computer Science and Engineering
June 2021

Rajala O., Kinnunen J., Särkiniemi M. (2021) Potential of Consumer EEG for Real-Time Interactions in Immersive VR. University of Oulu, Degree Programme in Computer Science and Engineering, 56 p.

ABSTRACT

Virtual reality is an active research subject and has received a lot of attention over the last few years. We have seen multiple commercial VR devices, each improving upon the last iteration become available to the wider public. In addition, interest in brain-computer interface (BCI) devices has increased rapidly. As these devices are becoming more affordable and easy to use, we are presented with more accessible options to measure brain activity. In this study, our aim is to combine these two technologies to enhance the interaction within a virtual environment.

In this study we sought to facilitate interaction in VR by using EEG signals. The EEG signals were used to estimate the volume of focus. By applying this concept with VR, we designed two use cases for further exploration. The methods of interactions explored in the study were telekinesis and teleportation. Telekinesis seemed an applicable option for this study since it allows the utilization of the EEG while maintaining a captivating and engaging user experience. With teleportation, the goal was the exploration of different options for locomotion in VR.

To test our solution, we built a test environment by using Unity engine. We also invited several participants to gain feedback on the usability and accuracy of our methodology. For evaluation, 13 study participants were divided into two different groups. The other group tested our actual solution for the estimation of the focus. However, the other group used randomized values for the same purpose. Some key differences between the test groups were identified.

We were able to create a working prototype where the users could interact with the environment by using their EEG signals. With some improvements, this could be expanded to a more refined solution with a better user experience. There is a lot of potential in combining the use of human brain signals with virtual environments to both enrich the interaction and increase the immersion of virtual reality.

Keywords: Virtual reality (VR), Brain-computer interface (BCI), Unity, Electroencephalography (EEG)

Rajala O., Kinnunen J., Särkiniemi M. (2021) Kuluttaja-EEG laitteiden potentiaali reaaliaikaiseen vuorovaikutukseen immersiivisessä virtuaalitodellisuudessa. Oulun yliopisto, Tietotekniikan tutkinto-ohjelma, 56 s.

TIIVISTELMÄ

Virtuaalitodellisuus (VR) on aktiivisen tutkimuksen kohde ja varsinkin viime vuosina herättänyt paljon huomiota. VR-laseissa on tapahtunut huomattavaa kehitystä ja niitä on saatavilla yhä laajemmalle käyttäjäkunnalle. Lisäksi kiinnostus aivo-tietokone -rajapintoihin (BCI) on kiihtymässä. Koska aivokäyrää mittaavat laitteet ovat yhä edullisempia ja kehittymässä helppokäyttöisemmiksi, monia uusia menetelmiä aivosignaalin mittamiseksi on saatavilla. Tässä työssä tavoitteemme oli yhdistää nämä kaksi teknologiaa parantaaksemme vuorovaikutusta virtuaalitodellisuudessa.

Tässä tutkimuksessa käytimme aivosähkökäyrää VR-käyttäjäkokemuksen kehittämiseksi. Tätä tekniikkaa hyödyntäen arvioimme käyttäjän keskittymistä. Tutkimusta varten valitsimme kaksi vuorovaikutustapaa. Nämä tutkittavat tavat ovat telekinesia sekä teleportaatio. Telekinesia on mielenkiintoinen tapa hyödyntää aivosähkökäyrää luoden samalla mukaansatempaavan käyttäjäkokemuksen. Teleportaation päämääränä oli löytää uudenlaisia liikkumistapoja VR:ssä.

Tutkimustamme varten, suunnittelimme testiympäristön Unity -pelimoottorilla. Kokosimme joukon testaajia, joiden avulla arvioimme työmme käyttökelpoisuutta sekä tarkkuutta. Saadaksemme luotettavampia testituloksia, jaoimme 13 testaajaa kahteen eri ryhmään. Toinen ryhmistä testasi varsinaista toteutustamme ja toinen ryhmä käytti satunnaistettuja keskittymisarvoja. Löysimme ratkaisevia eroja näiden kahden testiryhmän välillä.

Onnistuimme kehittämään toimivan prototyypin, jossa käyttäjät kykenivät interaktioon virtuaaliympäristössä hyödyntäen aivosähkökäyrää. Jatkokehitystä tekemällä käyttäjäkokemusta olisi mahdollista parantaa entisestään. Integraatio aivosensoreiden ja virtuaalitodellisuuden välillä huokuu potentiaalia ja tarjoaa mahdollisuuksia tehdä virtuaalimaailmasta yhä immersiivisemmän.

Avainsanat: Virtuaalitodellisuus (VR), Aivo-tietokone -rajapinta (BCI), Unity, Aivosähkökäyrä (EEG)

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FOREWORD

This thesis was done as part of Applied Computing Project course. As part of the course, we were presented with a list of project topics. The topic regarding VR and telekinesis drew our attention. The combination of virtual reality and brain-computer interfacing seemed really intriguing. The concept of using our minds to interact within VR environment was unique and aligned with our personal interests. We believe it has a lot of future potential for many different purposes, such as entertainment and research.

There were some challenges for us. We did not have prior knowledge of EEG and BCI, so we were treading on unknown territory. But since the subject seemed interesting, we decided to take on the challenge. We have had no regrets since we gained a lot of insight and it opened a whole new perspective of interacting with the virtual medium.

Many people have either helped or contributed to our thesis. We would like to thank Dr. Panos Kostakos and Dr. Paula Alavesa for being the supervisors for this thesis. We would also like to thank our families, friends, and all the people who gave feedback and were part of the study. We are glad that people showed a lot of interest and were able to participate in our evaluation study even during 2021 COVID-19 restrictions.

Oulu, June 9th, 2021

Oskari Rajala
Jere Kinnunen
Mikael Särkiniemi

LIST OF ABBREVIATIONS AND SYMBOLS

VR	Virtual Reality
BCI	Brain-Computer Interface
EEG	Electroencephalography
HMD	Head Mounted Display
NASA	National Aeronautics and Space Administration
LCD	Liquid Crystal Display
OLED	Organic Light Emitting Diode
CRT	Cathode-Ray Tube
IoT	Internet of Things
MQTT	Message Queuing Telemetry Transport
AR	Augmented Reality
MR	Mixed Reality
ERP	Event-Related-Potential
RFID	Radio Frequency Identification
NFC	Near Field Communication
BLE	Bluetooth Low Energy
LSL	LabStreamingLayer
SDK	Software Development Kit
API	Application Programming Interface
UI	User Interface
SSQ	Simulator Sickness Questionnaire
FFT	Fast Fourier transform
FPS	Frames Per Second
RGB	Red-Green-Blue

1. INTRODUCTION

Telekinesis has been a widely featured superpower in science fiction movies and comic books. Despite its eminence in popular culture, psychokinetic abilities have not been possible even in the entertainment industry. However, with modern technology, it is possible to simulate such skills in a virtual immersive environment by using brain-computer interface (BCI). Brain signals are a unique user input, which could provide a new modality of engagement and interaction. Furthermore, combining commercially available Virtual Reality (VR) and BCI devices can enable users to traverse and manipulate virtual worlds by purely using their minds.

The goal of the thesis is to build a second-generation prototype of a Unity program that gives telekinetic powers to a user in a VR environment using the Oculus Rift headset [1]. For the BCI, we will use a portable electroencephalography (EEG) device Muse 2 [2]. The idea stemmed from an existing first-generation prototype that already experimented with the connectivity between Muse 2 and the Unity game engine. After testing the previous prototype, we decided to start from scratch.

Figure 1. First generation prototype. Figure with permission[3]

1.1. Authors's Contributions

All three authors worked on this project equally. Work on the project spanned over six months. Everybody participated in the writing of the thesis, and the participants of the evaluation were recruited by each of the authors. There was no strict division of tasks, but some specializations formed which are shown in Table 1

Author	Contributions
Rajala Oskari	Unity design, Programming
Särkiniemi Mikael	Algorithms, Programming
Kinnunen Jere	Testing, Data analysis

Table 1. Authors' contributions

2. BACKGROUND AND RELATED WORK

Virtual reality and brain-computer interfaces are some of the most prominent topics of scientific interest in the modern technology-driven world. Both technologies have numerous fields of application and can impact many different fields of research across the board. Both have existed for a long time, but especially virtual reality has recently become widespread among the general populace. BCI has also been an active target of research in recent years. In the following chapters, we inspect them more closely along with related technology and projects.

2.1. History of Virtual Reality

Virtual reality has a rich history when it comes to devices and usage. Many of the first implementations of VR have stemmed from the need to deliver effective training and simulation environments. While the entertainment field has looked for new ways of stimulating the users' senses, the military had an early interest in VR for training pilots [4].

Society has always sought novel ways of creating more immersive virtual experiences. From simple panoramic paintings to modern Head-mounted displays (HMDs) we are seeking to deeply immerse the user into virtual worlds. HMDs particularly engage users compared to other methods, but until very recently the technology has simply not there in terms of computing power and availability[5].

Dating back to the early '60s, there have been multiple HMDs that incorporated VR-like elements such as the playfully named "Sword of Damocles" by Ivan Sutherland to more commercially available products like Nintendo's Virtual Boy. The early Sword of Damocles from 1965 was able to project a simple wireframe cube into a room. It was heavy and had to be suspended from the ceiling. Whereas Sword of Damocles lacked mobility, Virtual Boy from 1995 was a lightweight and compact package for its time. However, it came with the cost of missing all the movement tracking elements that we generally associate with VR today. Soon after it was launched, Virtual Boy received a lot of complaints of causing headaches. This is most likely caused by its black-red monochrome display[5].

However, there were multiple HMD devices that looked very similar to the VR products of today. Visual Programming Labs founder Jaron Lanier coined the term "virtual reality" in 1987. At the time VPL was the first company to sell virtual reality goggles. VPL's product, EyePhone, was a development towards modern devices. It had a specifically made glove that could be used as a controller. NASA's Project VIEW incorporated similar auxiliary gloves with a simulator meant to train astronauts in 1989. In 1991 The Virtuality Group launched several VR arcade games, some even having multiplayer features. Virtuality machines had a low latency between the user's head movements and corresponding imagery being displayed. However, the cabinets were large and the frames-per-second (FPS) would not stand up to today's standards[4].

Modern VR HMDs are inching closer to what Sutherland envisioned as the Ultimate Display: an experience so lifelike that you perceive the simulation as reality, as you would in a dream. Currently used LCD and OLED displays have replaced Cathode-Ray Tube (CRT) -based solutions, reducing the size and power usage greatly [6]. From superior image quality of devices such as Oculus Rift and HTC Vive Figure 2 to extremely affordable alternatives like Google Cardboard, we are finally able to reach an immersive virtual experience from the comfort of our homes[5]. HTC Vive uses room-scale tracking allowing more freedom of movement to the user. These experiences can be greatly enhanced by incorporating multi-modal input from other devices and sensors, creating an Internet of Things (IoT).

Figure 2. HTC Vive. Figure (c) Authors

2.2. Internet of Things and VR/AR

There is a broad range of potential implementations and use-cases for virtual reality enabled by the IoT. Such implementations include video games[7], professional training[8] and safety systems[9]. With free game engines like Unreal Engine and Unity, prototyping is cheaper and easier than ever before[6].

Researchers have found various use-cases of utilizing IoT in VR. Typically, the data is gathered from the user via external sensors. This often includes accelerometers and gyroscopes in order to discover the kinetic attributes of a limb[10] for example in simulating a training field for baseball practice in VR. To achieve this, researchers have used a digital instrumented glove containing necessary kinetic sensors to gain all the needed data for the movement in VR. Actuators, like an electric shock, were used to indicate the impact when the user hits the ball.

VR has been used to train humans in interfacing with other devices[11], exploring the possibility of using VR as an intermediate for training users to utilize a BCI device. In the first step, the users practiced controlling a virtual wheelchair only with a BCI device. After the training, they were able to move a real physical remote-controlled wheelchair with BCI. VR has also been proven to improve results in professional training[8]. Therefore, virtual reality likely increases the speed of the learning process for our BCI.

Information for extended reality (AR/VR/MR) can be gathered from external sources of the user. In these cases, we are often interested in environmental data like humidity and temperature. In AR it could be possible to display the data values visually to the user. For instance, [12] presented an IoT system for monitoring and controlling devices through mixed reality. For measurement, they used temperature, relative humidity, luminance and CO2 concentration sensors. The sensors were connected to a single-board computer with Message Queuing Telemetry Transport (MQTT) protocol. In the future, the system could get integrated into devices like iPad for displaying the data values.

AR-IoT systems can also be used to increase safety in a hazardous environment. [9] presented a safety system prototype that utilizes sensors and cameras for monitoring environmental properties like radioactivity. The actor is then warned if the limit is exceeded with a sound alarm. The data is also displayed to the user through HMD.

In video game implementations BCI devices could help to improve user experience regarding movement while traversing virtual environments. In 2020, video game developer Valve Software released Half-Life: Alyx. In this video game the user was able to select from three types of locomotion: i) Continuous movement, ii) Blink teleport, and iii) Shift teleport. With continuous movement, the player would move around the landscape at a steady pace using the controller's directional pad. With Blink teleport, the player would select a location to teleport to and the screen would briefly go black as the player was moved to the desired location. Shift teleport is almost the same as Blink teleport. Instead of the screen going black, the player would rapidly move to the forward position[13].

Some of these movements could produce cybersickness or more precisely visually induced motion sickness as the user's body is receiving conflicting information. Through the HMD user can visually perceive himself moving meanwhile the body is not experiencing any movement[14]. Many BCI devices are capable of detecting the user blinking. It would be possible to combine the two elements in a way that the player's character would move only when the player's eyes are either partially or fully closed, reducing the chance of motion sickness.

2.3. Brain-Computer Interfacing

Brain-computer interfaces refer to systems that connect external technology to the human brain. Adolf Beck in the 1880s managed to detect brain signals from animals by attaching electrodes directly on the surface of the brain[15]. Richard Caton had done the same observation couple of years earlier. Today, BCI Systems are grouped into invasive and non-invasive methods. With invasive methods, the signal is stronger, but the major disadvantages are that it requires major surgery on the subject which is risky and expensive. Proper research on invasive methods began in the 1970s when researchers in California performed tests on animals in search of new ways to externally communicate with the brain. Rapid development during the last thirty years in medicine and information technology has opened new possibilities for acquiring brain signals through safe non-invasive methods[16].

There exist several signal types for recording the electrical activity of the brain with EEG being the most commonly used type. It has a poor signal-to-noise ratio, but it offers a rapid resolution. [7] uses EEG for simple balance games. In the game, the user had to visually indicate which side the character would lean into to counter randomly generated movements. This shows it is possible to control the outcome of the game with only data gathered from the brain.

Since BCI brings the possibility of measuring cognitive states, the output effect from a measuring device could be more subtle and almost unnoticeable to the user. Whereas the input would not be a substitute for an interaction peripheral like a gamepad, it could complement the experience. For example, an EEG device could detect that the user is losing interest in the activity meanwhile the virtual world could adapt to better engage the user[7]. Seeking practical applications, researchers at the University of Tokyo used BCI and P300 signals to monitor drivers' awareness level in a simple virtual reality driving simulation[7].

Muse2 is a multi-sensor headband, which measures EEG, heart rate, breathing activity and body movement[2]. In our project, we are mostly interested in EEG, since it is needed for the telekinesis feature. Muse2 provides a non-invasive method for recording brain data, which means no invasive medical procedures are needed in order to use the device. The device weighs around 40g and the user can simply wear it while the data is recorded. Portable EEG systems like Muse2 can be used for visuospatial brain analysis[17]. Event-related potential can be measured with EEG. We possibly could utilize two components of the ERP, P300 and N200. Those are shown to be sensitive to the brain's attentional resources, which could be useful for indicating the desired direction of the movement in VR.

Figure 3. Muse2 BCI device. Figure (c) Authors

2.4. IoT and Bluetooth

Various technologies have evolved to enable communication between IoT- and smart devices. These typically include technologies based on radio frequency communication (RFID) like near field communication (NFC), which is capable of communicating a maximum of 4 cm distances. QR codes are also actively used as low-cost tagging [18]. Furthermore, perhaps the most widely known technology in this context is Bluetooth since almost all smartphones released in the last few years have some kind of Bluetooth hardware. The Muse2 headband uses Bluetooth to connect to an app on a smartphone.

Bluetooth low energy (BLE) is widespread technology among IoT. It was originally designed by Nokia under the name Wibree. Later it got integrated into the Bluetooth 4.0 specification. It is widely used in communication within relatively short distances and was designed with energy consumption optimization and cost-effectiveness in mind. The main difference to the typical Bluetooth is that it uses less energy, but is not capable of transmitting large amounts of data with minimal resolution, unlike conventional Bluetooth. BLE is useful for transmitting and recovering low-consuming data, for example, time or temperature, while preserving the battery of the device[19].

3. DESIGN

3.1. The Idea in a Nutshell

The framework of the functionality is relatively simple. The user wears a VR headset and Muse 2 headband simultaneously. One of the planned use cases is the ability to move objects via pseudo telekinesis. The VR headset is used to display the movable object to the user and to track the head movement. The Muse 2 headband is used to forward the EEG data to the Unity game engine. The object changes color based on the concentration of the user. After the concentration goes above a certain threshold, the user is able to control the object with head movement. Accordingly, the grip is lost if the concentration value goes below the threshold. A second use case is using the concentration value combined with pre-determined positions for teleporting the user around. Some important questions we seek to answer are as follows:

- How precisely are we able to determine a value representing the volume of concentration using Muse 2?
- How could we benefit from integrating EEG sensors into VR headsets?
- Could teleporting using the concentration reduce VR sickness compared to other methods of locomotion?
- How could EEG data be utilized in video games to enhance the user experience?

3.2. Use Cases

Both Oculus Rift and HTC Vive require the user to set up a physical play area while configuring the device. This is the area where the user will be using the device and the base stations can clearly track the headset's movements. The play area also works as a safeguard to prevent the user from bumping into household objects since the user is notified if they stray too close to the edges of the predetermined zone. The minimum play area for Oculus is 1m x 1m and for HTC Vive 2m x 1.5m. Vive's play area can be extended to a maximum of 10m x 10m by using four base stations. For home entertainment use, it is safe to assume that most of the users will have a play area with a size closer to the minimum end of the spectrum. While wireless options like Oculus Quest 2 is gaining popularity, most devices tether user to the computer with a cable, limiting mobility. This is why having many options for movement and interacting with far-away objects is important in a virtual reality setting.

3.2.1. Teleportation

There are many VR games and applications that can be experienced fully without needing to worry about locomotion. As the virtual environments get larger, the question of locomotion needs to be tackled. All movement is often done with the help of a controller. The joysticks and touchpads found in these controllers can be sensitive or bumped accidentally, causing unexpected movements. These sudden movements do not help as VR locomotion, in general, can be uncomfortable and requires getting used to. As the player sees movement through the VR headset but their body is experiencing none, movement in VR can cause nausea similar to seasickness.

Our motivation is to look for a new way to improve conventional teleportation techniques and explore an option that requires no controllers. The user should be in a certain state of mind or level of concentration to be able to teleport. The act of teleporting is instant and does not cause sudden accelerations. If in the future EEG and blink detection could be integrated into VR headsets, even the brief moments where player transitions from point A to point B could be disguised within a blink, thus reducing the possibility to cause further discomfort.

Our implementation is probably not suitable for all VR applications. Movement is the key in action and platforming games. Action games can be exciting and stressful, so any attempt to concentrate during a fast-paced sequence could be off-putting. For more calm situations this could be a plausible alternative to controllers. We also believe that eventually, the users can learn to teleport faster as they gain more experience with this implementation.

3.2.2. Telekinesis

One frustrating task that a player might encounter is having to physically bend down to pick up objects on the ground or reach for distant items within the limited play area. This is why it is important to search for more fluent ways of manipulating objects in VR settings. For example in Half-Life: Alyx, the developers created an in-game item what they called 'Gravity Gloves' that allowed the player to propel far-away objects towards the player's hand. Other implementations have explored ways of manipulating the posture of an object by combining controller inputs and head tilting, like the Jedi ForceExtension [20].

Our motivation is to implement the player's brain signals as input and explore the new possibilities this might bring up. Our implementation could leave the controllers free for other interactions and hand gestures. Telekinesis and controlling objects with one's mind is a well-known concept from fiction and thus could be seamlessly implemented into video game applications. As we believe that users can become more skilled with EEG-based features, the telekinesis interactions will become more fluent over time. Users could compete against each other on their skill of telekinesis and essentially their control of one's focus. Features like such can be also easily modified and expanded for further use cases.

3.3. Hardware and Software Requirements

Our implementation requires a Windows or Linux based machine that is capable of running Unity and VR programs. Officially recommended minimum hardware specifications for SteamVR are as follows;

- Processor: Intel Core i5-4590 / AMD FX 8350 equivalent or better

- Graphics card: NVIDIA GeForce GTX 970 / AMD Radeon R8 290 equivalent or better

However, our Unity environment was computationally very light. One of our modestly powered testing rigs was equipped with a GTX 660ti and a third-generation Intel i7 but was still able to run the tests with no noticeable drops in frame rates with VR. Also, the ability to receive Bluetooth data is vital to send EEG values between Muse 2 and the computer.

3.4. The Design in Detail

The goal is to experiment with two use cases: telekinesis and teleportation. Telekinesis enables controlling objects based on the signals coming from the brain, and teleportation is a form of instant locomotion from a point to another. Normally both teleporting and manipulating objects in the environment are done with controllers provided with the VR unit. We wanted to create a simple test environment in Unity with very few distractions, including simple textures, shapes and no audio ques.

After looking into some example Unity scripts and methods we decided that the simplest way to start testing both use cases would be to create an empty scene with a floating cube object that would somehow react to the values coming from the Muse 2 headband. We needed a new way of giving feedback to the user as this kind of object interaction is usually represented by the controllers' vibration motors.

The object in Unity needs to change in some way depending on the concentration of the user. The first idea was to change its opacity. The object could be more transparent if the user is not able to focus properly and vice versa. After consideration, we decided to use color, since we deemed it to be more visually exciting and appealing. The object would change its color in a red-green spectrum. Red means the user does not concentrate at all or the headband is not equipped. The color continuously changes to yellow when the user wears the headband and starts to focus. Then it changes to green when concentration is sufficient.

The values shown on the left-hand side of Figure 5 have the purpose of observing the received values from all the channels and the calculated Focus Value. These are tied to a Unity User Interface (UI) element called canvas and will not be seen by the user wearing the VR headset. They will be only visible through the Unity editor window where most of the environment screenshots are taken from. As of now, we do not plan on displaying the numeric value to the user as it would be distracting and it would defeat the purpose of having a color-coding for the objects.

The color is completely dependent on the focus value. The focus value needs to be calculated from the EEG data. In order to do this, we need to observe how the EEG stream behaves when the concentration changes. Based on that we decide what numerical properties are used for the algorithms we implement. Preferably the focus value could be something simple. For instance, it could be based on a 0-10 scale, zero being the least focused.

For better understanding, we set up an environment Figure 5 in Unity to observe the EEG values and adjust the focus value to be better suited for our project. We manually adjusted the algorithm until we were satisfied by how the focus value changed

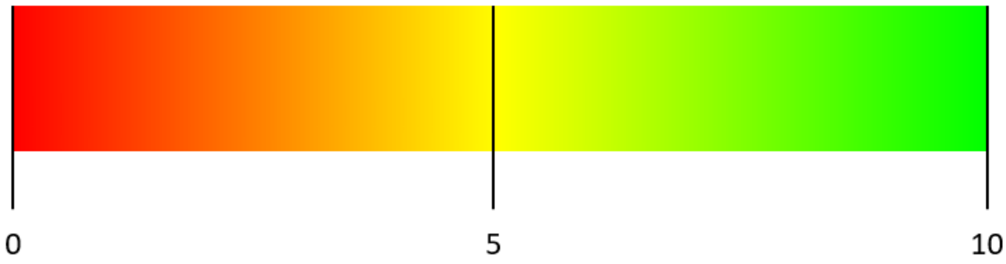

Figure 4. The desired color spectrum. Figure (c) Authors

according to the user's actions, which is explained in detail in the implementation section. Many actions such as moving eyes around or blinking will now quickly reduce the focus value.

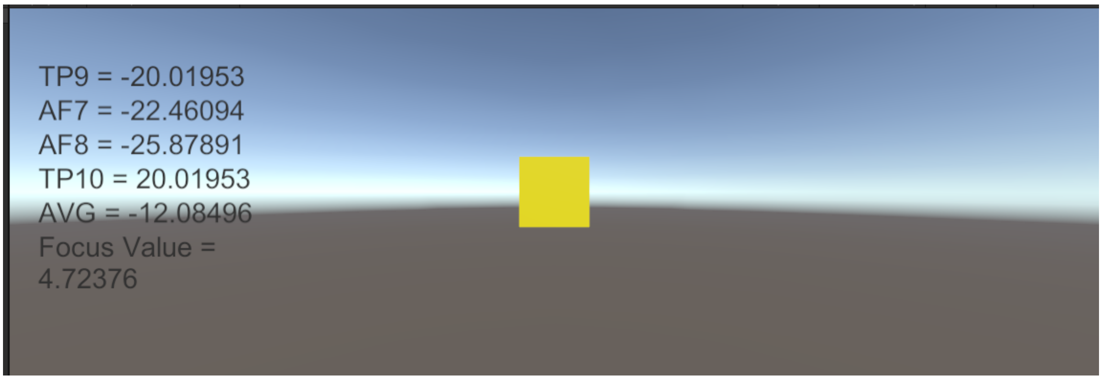

Figure 5. Our Unity environment to observe the values. Figure (c) Authors

We also needed a test environment to measure the functionality. We designed an environment that the user will have to navigate using the EEG data provided by Muse 2. The environment consists of multiple sets of teleportation destinations and targets to move objects into using the telekinesis feature. This environment was later used to perform the evaluation part of the project.

3.5. Utilizing BCI in Interactive Media

If the focus can be measured somewhat accurately the ideas for possible use cases are endless. These types of EEG sensors could be integrated into VR headsets, which could offer an even more immersive experience for the user. Even outside of VR, EEG data could be utilized in video games. Nowadays, depending on the video game, the "skill" is usually measured through the precision of clicks, reaction time and knowing the game mechanics. This type of technology could allow the ability to focus to be part of the skill. In competitive games, the volume of focus could benefit the player in some way, for example, the swaying of aim in a first-person shooter game. In Role-Playing

Games this could be implemented into magical powers where the most powerful spells would be conjured by players with the best concentration skills.

EEG data could be also used to enhance immersion. The output in a game could be affected by some attributes of the EEG stream. The atmosphere in a horror game could change depending on the mood of the player. This most likely requires a more in-depth analysis of the EEG, rather than only defining the volume of focus. Cheating with an EEG device is not as trivial as it would seem at first. The user can not maintain good focus values by improperly wearing or taking off the device. We observed that instead of flatlining, the EEG signals start moving sporadically between the minimum and maximum values when the headband was worn incorrectly and especially if not worn at all. On the other hand, this type of device most likely cannot be used in medical research. The sensors in Muse 2 produces too much noise compared to more expensive methods like placing the electrodes directly on the scalp of the head with the help of gel. This type of setup would be quite uncomfortable while playing video games.

Facebook showed interest in VR after acquiring the Oculus brand in 2014. After an announcement in 2017 Facebook Reality Labs has also worked on a BCI system that would let people write using their brain signals. Recent announcements in 2020 indicated that their brain-to-text decoding system was able to reach very low error rates with a vocabulary containing up to 300 words [21]. Facebook certainly has both elements in its grasp to redefine VR experiences by combining it with elements of BCI.

Nonetheless, EEG implementations in video games are still a very unexplored area and would certainly give players a completely new peripheral to experiment with. Valve's co-founder Gabe Newell has taken a particular interest in BCI and Valve has been testing different applications with OpenBCI, which is an open-source platform for biosensing tools. Newell implied that video game developers would be making a mistake by not looking into BCI in the near future. According to Newell a lot of the discussion around possibilities of BCI is quote "indistinguishable from science fiction," but he also reminds that a lot of focus has to be put on the security of the devices. Even one bad experience stemming from a data breach or hacking incident could shy away future user acceptance [22].

4. IMPLEMENTATION

4.1. Setup

4.1.1. Equipment

Muse 2 is a headband developed by InteraXon and has various sensors embedded within including an accelerometer, gyroscope, pulse oximeter and EEG sensors. Various signals are collected via contact plates that sit against one's forehead. The device is mainly advertised as a tool for meditation purposes. The user would connect their device via Bluetooth to their mobile phone and headphones. Muse would then give sound cues to the user by translating the user's amount of brain activity into different sounds of weather. Data can be gathered via a downloadable phone application, making the device a relatively cheap non-invasive BCI device[2].

Oculus Rift is a virtual reality headset made by Oculus VR. Oculus Rift was originally a project that started from crowdfunding website Kickstarter in 2012 and saw a commercial release in 2016. It connects to a PC via two USB cables and an HDMI cable that is plugged into the graphics card of the computer. The whole package consists of the headset, two controllers and two Oculus Sensors. These two sensors track the movements of the headset using infrared LEDs and allow a full 360-degree room-scale experience with six degrees of freedom for the user. The headset has a dual OLED display with a resolution of 1080x1200 and a 90hz refresh rate[1].

Figure 6. User wearing the Muse2 and Oculus Rift devices. Figure (c) Authors

4.1.2. Software and Libraries

Our project uses multiple different 3rd party software and libraries to accomplish different tasks. These include tasks such as networking and creating the virtual environment. Table 2 lists all the used software and libraries.

Software name	Purpose in implementation
Blue Muse	Bluetooth connectivity for Muse 2
LabStreamingLayer	API connecting Unity and Muse 2
BrainVision LSL Viewer	Observing of EEG values
Unity	Creating the virtual environment
SteamVR	HMD functionality in Unity

Table 2. Used software and their roles

BlueMuse is a software that allows the connecting and streaming of data from Muse devices to Windows 10. It works using a library called LabStreamingLayer. Supported forms of data from Muse devices are EEG, PPG, accelerometer, gyroscope and telemetry data[23]. Our project uses BlueMuse to connect our Muse 2 device and stream EEG data to the computer via Bluetooth. We chose BlueMuse over the official software, Muse Direct, because it was only available for iOS devices. InteraXon had also stopped offering the Muse Software Development Kit (SDK).

LabStreamingLayer is a distribution that includes its core library and multiple tools built from it. It is a system that can handle the measurement of different devices and handles the networking, real-time access and time-synchronization of the data. It is used to create a local network called a lab network that allows communication of different kinds of software through the use of the library[24]. In the project, LSL is used to allow the transfer of data from BlueMuse to Unity3D. This works through an LSL Unity plugin.

Brainvision LSL Viewer is a tool released by Brain Products for monitoring online LSL streams. It is able to visualize up to 32 EEG channels simultaneously and display Fast Fourier Transforms for four channels. Not only EEG signals, but any data stream with regular sampling intervals from a device using LSL can be monitored and recorded[25]. In the project, this was used for analyzing the four channels streamed from Muse 2 during different interactions. LSL Viewer was also very useful for calibrating the device when making sure that the Muse 2 headband was in the correct position and it was getting proper contact on the user's forehead.

Unity is a real-time development platform for 2D and 3D development. It is a cross-platform 3D game engine that includes its own IDE. It is programmable via C# and the Unity Scripting API. Unity allows the easy testing of projects via its runtime without having to manually compile the project multiple times[26]. Our project uses Unity for creating and rendering the virtual environment to interact in.

SteamVR is a runtime included with digital video game distribution service Steam. SteamVR has been developed by Valve and currently supports multiple popular virtual reality gaming devices including Valve Index, HTC Vive, Oculus Rift and Windows Mixed Reality headset. It automatically installs itself for Steam users if it detects that a VR device is connected to a computer[27]. A Unity Plugin was used to interface SteamVR with Unity. This allows the Unity project to work with any SteamVR Application Programming Interface (API) compatible VR device[28].

4.1.3. Connections and Networking

The first part of our project is to connect the Muse 2 Device into Unity and stream data. This cannot be directly achieved, since the Muse 2 cannot be natively connected to the PC preventing communication with Unity. We designed a solution shown in Figure 7 that utilizes BlueMuse and LSL to connect our Muse device to Unity.

Figure 7. Network connecting Muse 2 to Unity. Figure (c) Authors

In the first step, our solution uses BlueMuse to connect the Muse2 device to Windows 10 via Bluetooth. Then the BlueMuse software streams the data from the Muse2 to a local lab network created by BlueMuse using LSL. This network has 4 channels that include a set of EEG data giving us 4 points of data: TP9, AF7, AF8 and TP10. This network allows interfacing of other software using the LSL library. Our Unity project has an LSL plugin allowing interfacing with the local lab network. Via this network, we are able to stream data from BlueMuse to Unity.

4.2. Processing the Data

4.2.1. Technical Evaluation of the EEG

Muse 2 EEG sensors measure brain activity in 4 channels. Although not required, we use 3rd party software "BrainVision LSL viewer" to show the EEG data on a computer screen. This helps to visually see the data and evaluate the amount of noise of each channel. It’s quickly noticeable that Muse 2 is not perfectly accurate and the signal/noise ratio is relatively high. This was strongly affected by the physical placement of the headband and possibly by the Bluetooth connection. We noticed that the channel, which received the most amount of noise switched on different occasions. The precision still might be sufficient for the success of our tasks, which includes the rough estimation of the focus of the user.

Our initial hypothesis was that the average amplitude and instability of the EEG on each channel are reduced by concentrating or moving more. This phenomenon can easily be seen in the Figure 8. Based on the sample size of 3, this clearly seemed to be the case. We decided to use this behavior of the EEG stream to determine the amount of concentration the user currently has.

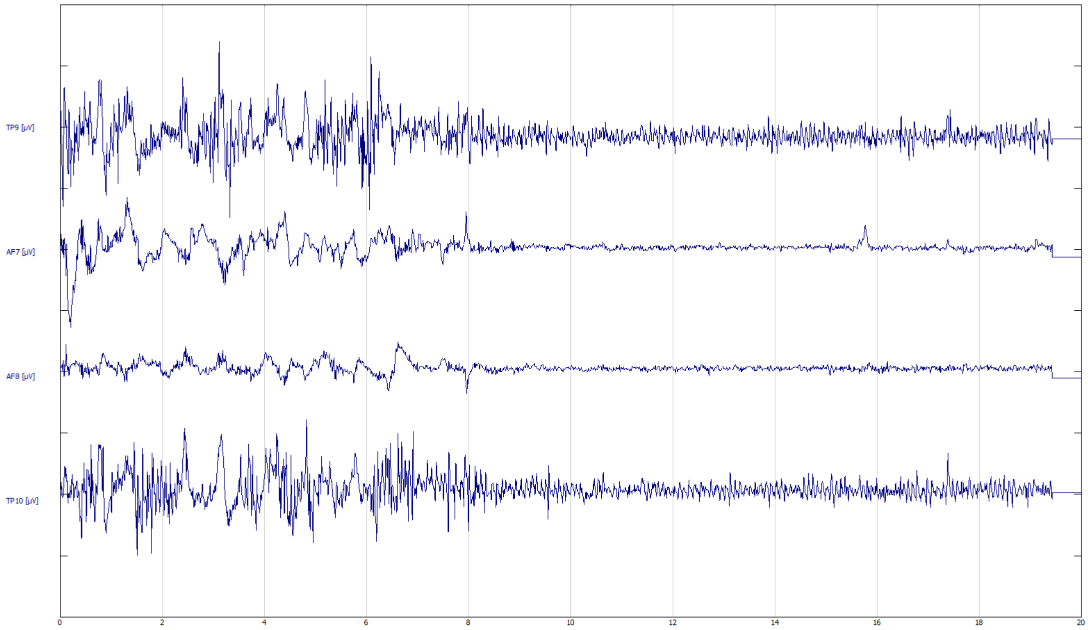

Figure 8. Sample EEG output when user goes from an "agitated" state to a "focused" state. Horizontal axis represents time and vertical axis represents changes in microvolts received from each of the four channels. Figure (c) Authors

4.2.2. Simplifying the EEG

To simplify the calculations of the focus value, we needed to represent the data of the channels as one entity. In order to do this, we need to accept that we can not shape the focus value based on an attribute of an individual channel. We calculated the average of the channels, which will be used to conclude the focus value. This was simply done by summing the channels and dividing the sum by four with a frequency of 10Hz.

Simplifying the channels to averages has its cons and pros. Since the channels are no longer separated we are unable to use the behavior of certain channels to determine the different attributes of the concentration. On the other hand, this method offers us to process the EEG as one value. When Muse 2 was placed in a visually correct place, there was usually zero, but sometimes one channel, which received a noticeable amount of noise. Because of this, using the channel averages partly diminishes this factor since the noise ratio is lower when it is compared to all 4 channels.

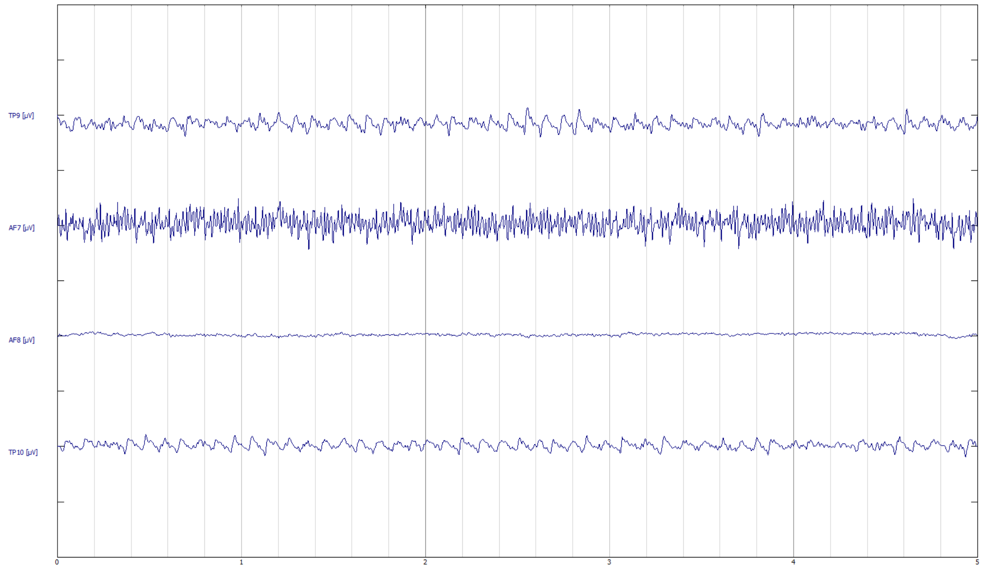

Figure 9. Sample EEG output with noise on the second channel. Figure (c) Authors

4.2.3. Processing the Averages of the EEG Channels

We need to decide which attribute of the continuous stream of averages could be used to determine the focus value. Since the averages fluctuate more or less based on the concentration and movement, we need to find a good mathematical concept to represent the fluctuation numerically. We decided to use standard deviation. To calculate this we need several averages. For the stability of standard deviation, we decided to use 100 averages, but we might consider changing the number in the evaluation section.

After calculating the averages we repeatedly store them into C sharp float list. In the first version of the algorithm, we calculated the standard deviation after every 100 averages and cleared the list after that. However, we realized there was a better but more complex method. In the second version, we decided to update the standard deviation every time an average is calculated. In addition, instead of flushing all the values, the list would work in the first-in-first-out principle when the list is full. This way the standard deviation is more stable and updated more frequently, leading to smoother color transforms.

$$y = \sqrt{\frac{\sum X^2}{N} - \mu^2} \tag{1}$$

Parameters for Formula 1: y=standard deviation, X=average of the 4 channels (every average in the list are squared and summed), N=the length of the list(always 100 in this case), μ=mean of the list of averages.

4.2.4. Determining a Refined Value for Concentration

The standard deviation of the averages seemed to be a suitable property. Its value approached zero when more focus is achieved and vice versa. Although this value could be the "focus value" itself, we wanted to refine it to make it simpler to understand and easier to be used in changing the color. This is why we calculated it to be based on a 0-10 scale. This was done by made up a function where the input is the standard deviation and output the focus value. The function could not be linear since lowering the standard deviation by concentrating got more difficult as it approached zero. A Sigmoid-like function seemed to be fitting since it is constrained from above and below by two horizontal asymptotes. In this case, we want them two be y=0 and y=10. In addition, it isn't linear.

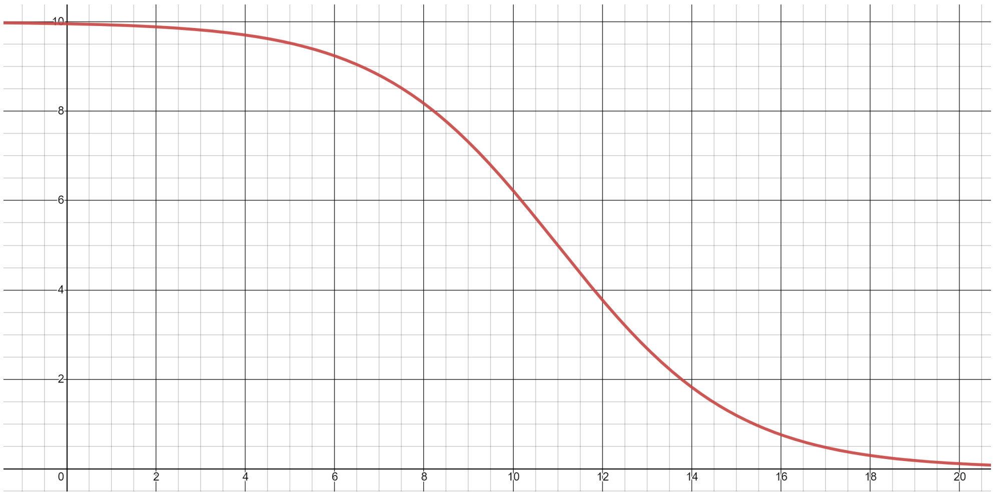

Figure 10. X=standard deviation, Y=focus value. Graph plotted in Desmos. Figure (c) Authors

Adjusting the inflection point of the function needs balancing. Based on the standard deviation values we achieved, around y=11 seems quite reasonable. This might need further testing during evaluation. The function and its graph can be seen in Figure 10 and Equation 2.

$$\frac{10}{1+e^{\frac{(10x-110)}{20}}} \tag{2}$$

4.2.5. Representing the Focus by RGB Values

Now we are able to represent the focus value by color. The object, which the user focuses on, changes color based on the focus value. The colors are based on a red-green spectrum, and they are handled as red-green-blue (RGB) values in Unity. When the focus value is 0, the user doesn't concentrate at all or the headband isn't equipped. In this case, the corresponding color is red (255,0,0). As the focus increases the RGB values approaches towards yellow. When the focus value is 5, the object is yellow (255,255,0). From value 5 to 10 the color transforms to green (0,255,0). For manipulating the RGB values we designed 2 linear functions. The other changes the color from red to yellow, and the other from yellow to green. By using two if-statements and those functions we were able to change the color accordingly.

Algorithm 1. Adjusting RGB values according to focus values. fv = focus value.

```
Function focusValueToRGB (float fv) :
    if fv < 5 then
        RGBvalues[0] = 255;
        RGBvalues[1] = (fv*51);
    else
        RGBvalues[0] = 510-51x;
        RGBvalues[1] = 255;
    end
    return RGBvalues;
```

4.3. Implementing the Use Cases

4.3.1. Telekinesis

The telekinesis system requires several sources of data. We have the focus value derived from the EEG values, the RGB values calculated from the focus value and the orientation data provided by the VR HMD. By utilizing all of these we created the mechanics for our telekinesis implementation. This was packaged as a class in Unity that could be attached to any objects we wished to be movable.

The class is composed of certain functions. There is a method using the ray system of Unity to detect if a particular object is in the center of the user's gaze. If this is true, the object will be highlighted with the color representing the focus of the user. This gives the user feedback on which object is being stared at and how focused the user is. If the focus value of the user is over 6 the object will start following the user's head movements at a predetermined distance. If at any point the focus of the user drops below 6 the object will be dropped and it will be subject to the game physics.

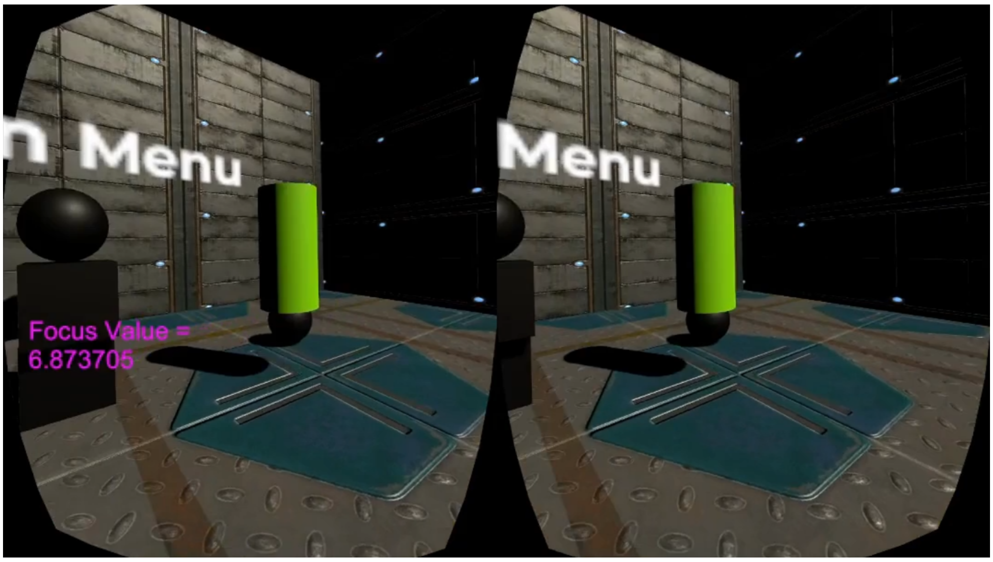

Figure 11. User moving an object in VR view. Figure (c) Authors

4.3.2. Teleportation

For the implementation of the teleportation feature, we used much of the same data as in the implementation of the telekinesis system. We once again used the focus value as well as the gaze detection system. The focus teleportation locomotion is limited to predetermined teleport nodes. To teleport the user must stare at a teleportation node for 5 seconds with a focus value of over 6. If the focus drops below 6, the timer for the teleportation is reset, and the user must attempt to refocus. The timer is represented to the user visually via color. The color of the teleportation node changes from red to green as time progresses.

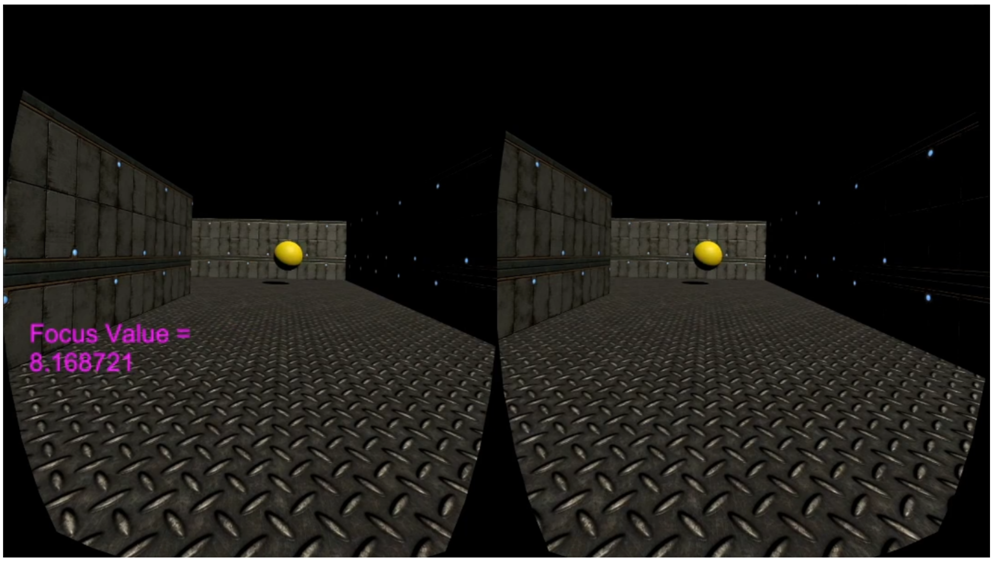

Figure 12. User focusing on a teleportation node. Figure (c) Authors

5. EVALUATION

In this section, we will investigate how well our implementation fills the goals of our project. We sought to create interactions in a VR space using a BCI device. Our evaluation should therefore quantitatively measure the usability and accuracy of our solution. We also asked the participants questions about their feelings during the evaluation and opinions regarding this type of technology.

5.1. Interaction Protocol Overview

The next step was to create a virtual environment that estimates the accuracy and usability of our project. Therefore, we designed a layout for the environment which is seen in Figure 13. The Playroom contained physical objects interactable with telekinesis. This room was used to teach the user how they are able to move the objects by focusing. Here we could also see if the Muse2 is correctly placed with the help of BrainVision LSL Viewer.

After the user was ready, they would proceed to the teleportation environment. Here they must proceed through a corridor only by using the teleportation system. The environment consisted of 5 teleportation nodes. The completion time and the EEG was recorded. After finishing, the user completed the game again. This time the completion is restricted by a time limit, which was visually shown to the user.

After the teleportation test, the user faced a basic puzzle. In this puzzle, the users needed to place certain shaped objects to their corresponding positions. These positions were indicated by table-shaped pedestals. Above the pedestals, a text was shown informing the needed shape. The pedestal transformed to green when the correct object was placed on it. When all the objects were correctly placed, the puzzle was finished. The completion time and the EEG were recorded.

After the tester was done with the evaluation game, they filled a survey. The survey contained both scored and open-ended questions. We asked the user various questions such as the occurrence of VR sickness, the functionality of the mechanics and the accuracy of the focus value. We were also interested if previous VR experience will affect user performance and experience. Users could also voice their opinion if they can see similar functions implemented into future applications and would they be interested in using those features if they were available.

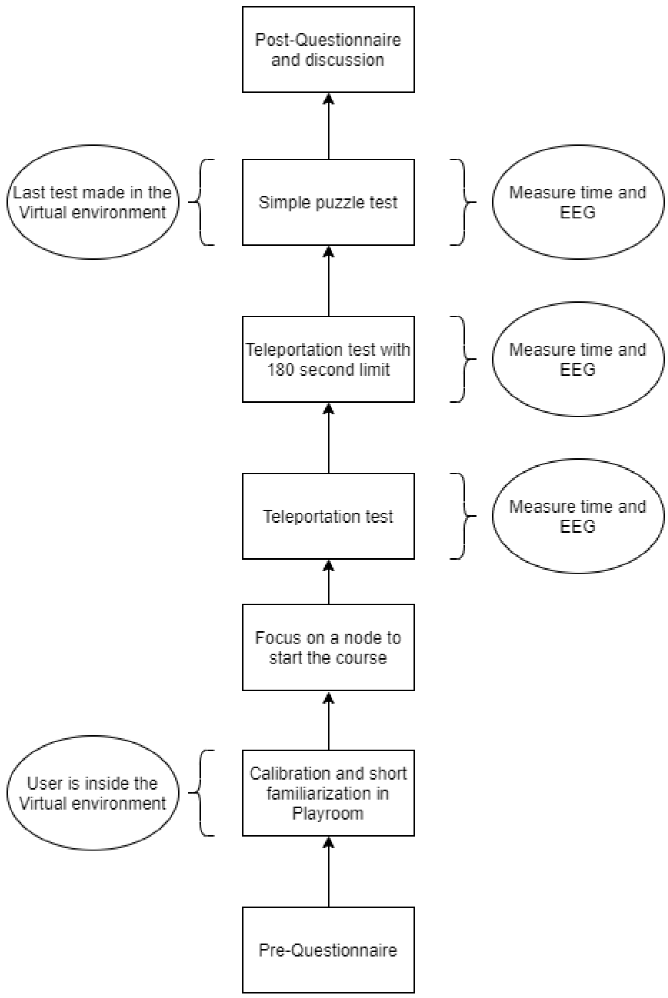

Figure 13. Figure showing the layout of our evaluation sequence. Figure (c) Authors

5.2. The Evaluation Procedure in Detail

Because of the 2021 COVID-19 situation, the tests were held in the authors' homes and none of the participants were randomly chosen. The test took approximately 20-30min including filling the questionnaires. Firstly, the participants were asked for their consent. This included saving the data from EEG and questionnaires, completion times and possibly recording the computer screen during the evaluation course. The participant was asked some basic information and background with VR and video games. The participants were also told some basic information about the project and evaluation. Each of the participants read through written instructions explaining each stage of the test while asking questions if needed. Next, we attempted to get a good signal from Muse 2. This might take some time because the placement of the devices has to be precise. After the signal is sufficient, the user would mount the Oculus headset and proceed to the playroom. Here they can freely move the objects around, to get a basic understanding of how the project works. Here it was also made sure that the user had not knocked the Muse 2 headband out of place while mounting the headset and that the user was able to achieve a wide range of focus values. This was done by observing if the user was able to focus and manipulate objects in the playroom. After getting comfortable, the participants were told they could start the evaluation course by focusing on a particular floating node in the playroom.

During the game, one of the authors was always available. It was important to visually monitor the EEG in case of noise and connection problems during the simulation. The evaluation game is described in the previous subsection. The simulation could be restarted in case of unexpected interrupts including crashes and could always be instantly stopped if the tester wanted so, for example in case of a strong feeling of VR-sickness. Participants were informed they could voice their thinking process during the experiment.

After the end of the game, the participant attended a survey that will contain mostly disagree-agree questions on a scale of 1-7. The feeling-based questions included topics regarding previous experience with VR, nervousness during the test, and the occurrence of cyber-sickness.

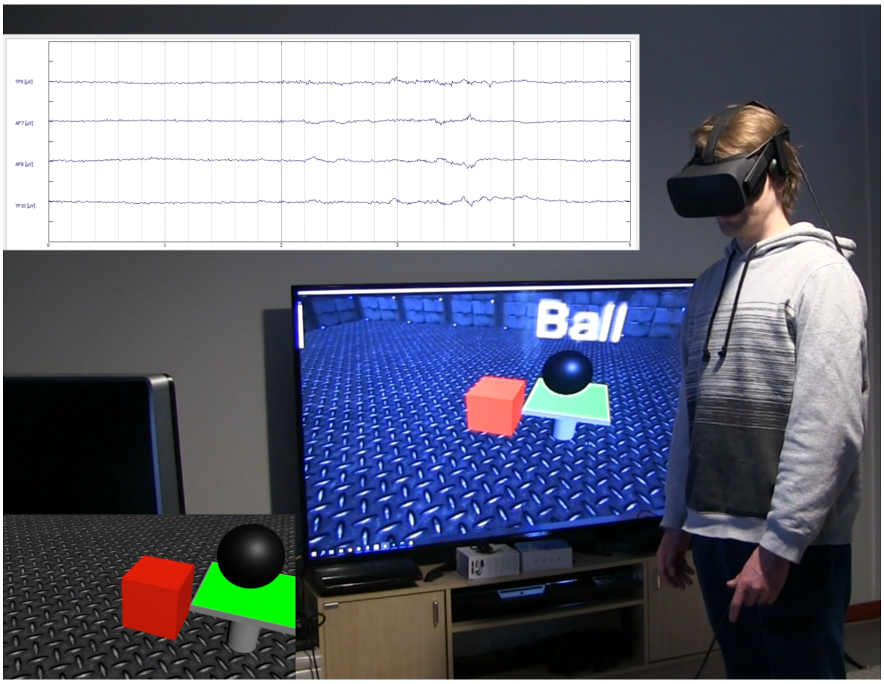

Figure 14. Participant during the evaluation procedure. EEG graphs and virtual environment screen superimposed. Figure (c) Authors

5.3. Test Groups

The testers consist of two test groups. The first group tested the system as it is designed, but the other group used randomly generated focus values. This was done to have comparisons on opinions between the real and fake systems. The focus generator only affects the color and, therefore, the interaction with the objects. The participants saw only the color and not the numerical values of the generation, as with the "real" focus values too. Otherwise, the randomization would be too obvious to notice. Even though the virtual environment uses the randomly generated focus, the EEG is recorded as normal. This allows comparing the "real" focus values between the test groups.

The randomization system works by giving random focus values from 0 to 10 between randomized periods. It is implemented by assigning "short term" and "long term" focus values. The short-term focus values change between 0.8 and 2.5 seconds. These can range between values of 3 and 7. Due to how the teleportation mechanics work, the generator also has a long-term timer that guarantees good focus for 6 to 7 seconds every 8 to 10 seconds. The behavior of the randomization can be further seen in Algorithm 2. We hypothesized that this would make the control group have better times in the teleportation tests. Designing the randomization to be too slow might cause more people to notice they are not actually testing the real system.

Algorithm 2. Algorithm used to generate focus values for the control group

```
goodFocusTimer = 5;
shortTimer = 0;
longTimer = 6;
timer = 0;
while True do
    timer += deltaTime;
    if goodFocus == true then
        longTimer -= deltaTime;
        shortTimer -= deltaTime;
        if longTimer <= 0 then
            goodFocus = false;
            goodFocusTimer = Random(8-10);
        end
        if shortTimer <= 0 then
            shortTimer = Random(0.8-2.5);
            focus = Random(6-10);
        end
    else
        shortTimer -= deltaTime;
        goodFocusTimer -= deltaTime;
        if shortTimer <= 0 then
            shortTimer = Random(0.8-2.5);
            focus = Random(3-7);
        end
        if goodFocusTimer <= 0 then
            focus = Random(6-9);
            goodFocusTimer = Random(6-7);
            goodFocus = true;
        end
    end
end
```

The focus value differences between these groups can be seen in Figure 15. These values are taken from the teleport test. At the beginning of the blue graph, the sharp fall of the focus values is caused by the fill of the sample buffer (100 values). After that, we can see the participant focusing and staying focused for long periods of time to teleport. Focus can also be seen dropping when the subject is looking around.

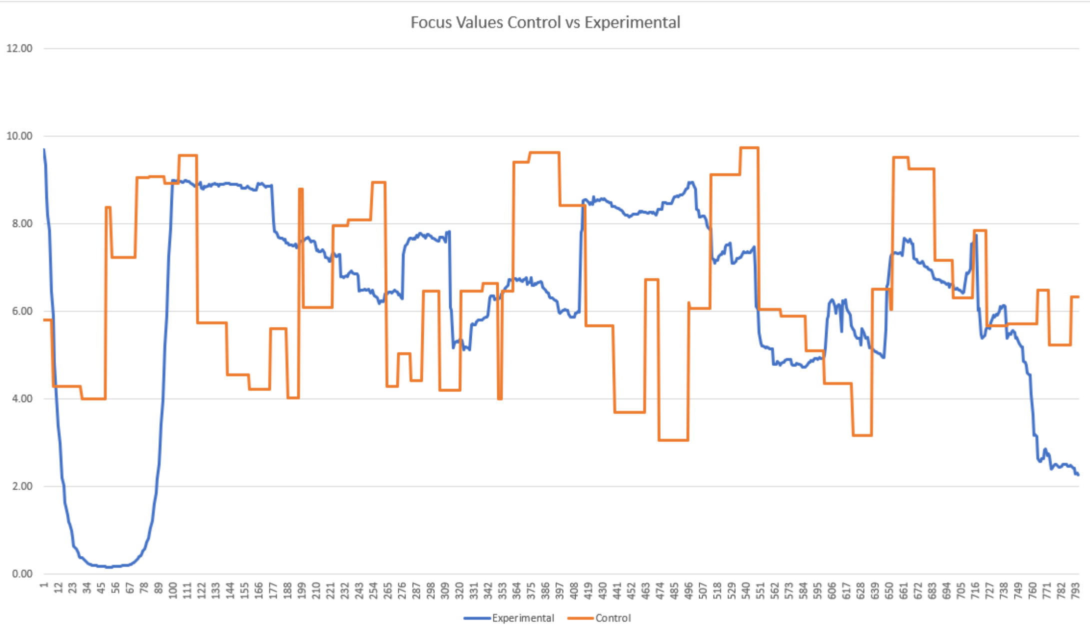

Figure 15. Orange shows sample of randomly generated focus values. The blue shows the typical behaviour of the "real" focus value. Figure (c) Authors

5.4. Defining the Relevant Information

For the evaluation, we gathered two basic types of data. This included subjective data which is based on participant's experiences, feelings and opinions on our project and the usability of EEG sensors in the video game industry. The second type of data we were interested in is the recorded data, which includes the values of EEG and the completion times during the course.

The recorded data will be analyzed afterward. One element we are interested in is how accurately does the standard deviation corresponds to the real value of focus. Determining this will require observing the similarity of the focus values between the users and between the test groups. The absence of similarity indicates (but doesn't prove) some of the following conclusions: the focus value we calculated is heavily dependent on the person, the low quality of the connection or the placement of the devices, or the inaccuracy of the Muse2 device or our algorithms. The opinions and the EEG values between the test groups could also inform more about the accuracy. The recorded focus values could also differ between the control group and experimental group by some other factor.

With the questionnaires, we tried to determine all the factors which could possibly have an effect on the results. In the pre-questionnaire, we gathered information about the backgrounds of the tester. In the post-questionnaire, we asked the participants for more detailed opinions about the project, the usability of EEG sensors and possible use cases in video games. This hopefully gives us a rough overview of the potential of this type of technology.

With the questionnaires and the evaluation game, we aimed to find out correlations between certain user factors. We were interested in how, for example, the experience with VR might affect the evaluation course results. Other factors include age, gender, color blindness etc. Because of the small sample size during the epidemic, any of the results will not probably be statistically significant.

6. RESULTS

The test groups had a total of 13 participants. There were 7 subjects in the control group who controlled objects with the randomly generated focus values. The other 6 subjects tested the actual focus value algorithms. The participants were aged from 21 to 58 years old (Mean = 35.5, Standard Deviation = 15.7). Due to restrictions caused by COVID-19, all the participants were familiar to the authors and the tests were held in semi-controlled environment in three different locations with different systems. Similar model of Oculus Rift and Muse 2 were used across all tests and the procedure protocol is described in section 5. The procedure was performed by same instructions with every participant.

6.1. Background of the Test Groups

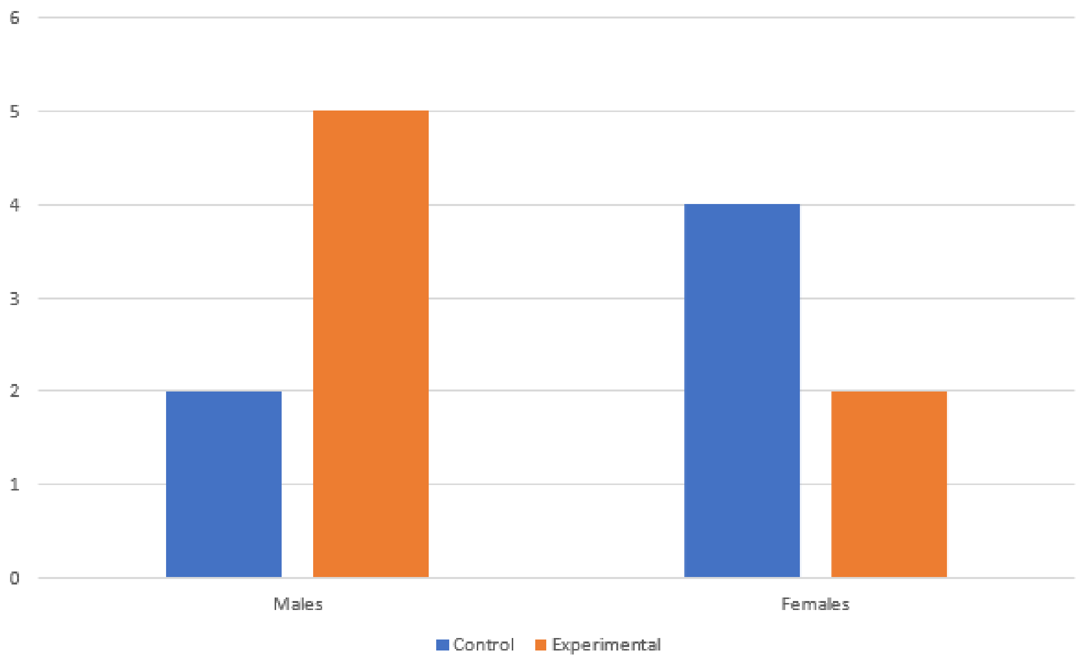

Figure 16. The gender difference between the groups. Figure (c) Authors

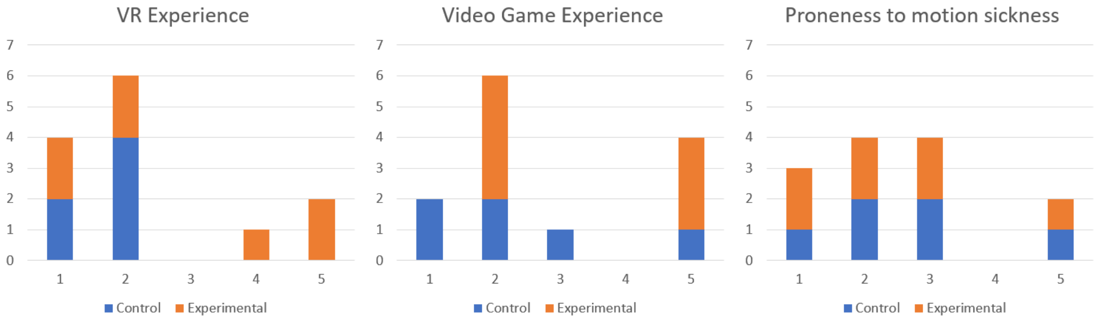

Figure 17. Answers regarding VR and video game experience, and proneness to motion sickness (scale of 1-5). Figure (c) Authors

6.2. Simulator Sickness Questionnaire

After finishing with the experiment, the participants filled a standard Simulator Sickness Questionnaire. The values are represented in Table 3. To qualify the results we performed a non-parametric Kruskal-Wallis test on them[29]. P-values indicate how statistically significant the results between the experimental and control groups were.

Group	Measure	Mean	Variance	p-value
Control	Nausea	15,9	242,69	0.942
	Oculumotor disturbance	27,79	337,07	0.311
	Disorientation	44,08	1194,89	0.132
	Total Simulator Sickness	33,66	581,88	0.283
Experimental	Nausea	14,99	208,02	0.942
	Oculumotor disturbance	18,40	169,63	0.311
	Disorientation	15,90	156,85	0.132
	Total Simulator Sickness	20,83	190,49	0.283

Table 3. Mean focus values and their standard deviation during different parts of the course

6.3. Recorded Focus Values and Completion Times

The EEG of the participants was recorded during every part of the game. Determining the focus value from the EEG were done afterwards with the same algorithms as before. The mean focus values are represented in Table 4. To qualify the results we analyzed the results using one-way ANOVA. All the results had p-values of less than 0.05, so they were all statistically significant.

Mean Focus	Control ($\bar{x}, \sigma$)	Experimental ($\bar{x}, \sigma$)	p-value
Playroom	(0.39, 0.41)	(2.10, 0.87)	0.004
Teleportation	(1.23, 1.63)	(4.11, 1.19)	<0.001
Timed Teleportation	(0.96, 1.10)	(4.22, 0.97)	<0.001
Puzzleroom	(0.27, 0.29)	(3.54, 1.18)	0.004
Whole course	(1.13, 1.28)	(3.94, 0.48)	0.007

Table 4. Mean focus values and their standard deviation during different parts of the course

The completion times for every part of the course was collected. The mean values of the times are represented in Table 5. To qualify the results we performed a non-parametric Kruskal-Wallis test on them[29]. We had two statistically significant results of p value being less than 0.05; the Playroom, the timed teleportation and the overall course times.

Mean Times	Control ($\bar{x}, \sigma$)	Experimental ($\bar{x}, \sigma$)	p-value
Playroom	(62.01, 35.68)	(223.58, 161.42)	0.045
Teleportation	(101.35, 30.15)	(95.26, 69.61)	0.567
Timed Teleportation	(79.01, 12.38)	(69.61, 25.82)	0.0321
Puzzleroom	(54.39, 20.21)	(107.89, 95.50)	0.567
Whole course	(297.75, 62.12)	(496.36, 148.50)	0.022
Whole course Without Playroom	(234.74, 23,88)	(272.77, 95.32)	0.567

Table 5. Mean times in seconds and the standard deviation to complete different parts of the course

6.4. Post-Questionnaire

After collecting the answers of post-questionnaire we were left with the results shown in Table 6. The results were evaluated using non-parametric Kruskal-Wallis test [29]. We were unable to find statistically significant results. However the Teleportation category of the results gave us almost significant results with a p-value of 0.071. With more participants we might have been able to reduce the p-value enough to make the results statistically significant.

Category	Question	Control ($\bar{x}, \sigma$)	Experimental ($\bar{x}, \sigma$)	p-value
Telekinesis	I was able to interact with the environment the way I wanted to.	(4.66, 1.50)	(4.71, 0.95)	0.613
	The color of the objects represented my concentration accurately in the puzzle room	(5.33, 1.75)	(4.57, 1.51)	
	The puzzle task was (1 difficult, 7 easy) to perform	(5.5, 1.22)	(5.28, 1.88)	
	Did you gain enough feedback for your actions in puzzle room?	(5, 1.78)	(5.57, 1.511)	
	It was easy for me to maintain focus while controlling objects	(6, 1.26)	(5.42, 1.39)	
Teleportation	I was able to interact with the environment the way I wanted to.	(6, 0.89)	(4.71, 1.11)	0.071
	The teleportation task was (1 difficult, 7 easy) to perform	(5.83, 1.32)	(4.85, 1.57)	
	The color of the objects reflected my level of concentration accurately in the teleportation room	(5.16, 2.13)	(4.57, 0.97)	
	Did you gain enough feedback for your actions in teleportation room?	(5.33, 1.75)	(5.42, 1.61)	
	I felt the time limit effected my performance in the teleportation room (1 worse - 7 better)	(5.33, 1.03)	(4.85, 1.86)	
General Questions	How was the length of the test? (1 short - 7 long)	(3.33, 1.21)	(3.14, 1.06)	0.292
	Did you find teleportation and telekinesis entertaining?	(6, 1.09)	(5.85, 0.69)	
	Did you find it comfortable to wear both Muse 2 and VR headset at the same time?	(5, 1.41)	(3.57, 1.98)	

Table 6. Results from the Post-Questionnaire. Participants gave an answer to each question within a scale of 1-7

6.5. Other Observations

There were some differences between the test locations. Although we used the same model of Muse 2 and VR headset, the PCs and the test environment were different in each location. One of the authors had quite old graphics card and had problems running the default Oculus VR environment. But the virtual environment in the evaluation course was lightweight enough to cause no problems with the FPS during the test. The test locations also significantly affected the quality of Bluetooth reception. One of the test sites had a particularly bad reception.

Participants were not able to wear eyeglasses at the same time as VR headset and the Muse 2. Due to this, some participants who wore eyeglasses said they had difficulty seeing objects in the environment. This was made worse by the fact that the VR devices were not fine tuned for the participants using the Oculus Rift's own calibration features.

After finishing the simulation and filling the post-questionnaire, the usage of the randomized focus values for the control group was revealed. Next, we gathered some anecdotal information from them. Some seemed to be most suspicious of it when trying to release grip of the objects with telekinesis. According to some people, during the teleportation tests the randomization is not that clear because the colour changes smoothly even with the randomization unlike during telekinesis. In the control group, some people claimed that they were not sure how the focus "should" actually behave. This might create a trust bias towards the system. Participants sometimes reasoned why they were not able to consistently achieve good focus values and, for example, put it on having a tiresome workday.

Some participants from the experimental group figured out a specific method to release a grip from an object. Two participants told us that blinking was a good method to drop objects. One participant from the experimental group thought that it was easier to increase focus values by observing the edges of an object instead of the center.

7. DISCUSSION

The thesis presents an explorative study into the subject of using commercial BCI devices and commercial HMDs to achieve an interaction in VR. There was no exact study to compare our results to. We came up with our own experimental protocol along with using some standard evaluation methods such as SSQ. The number of conclusions from the data is therefore limited, but there was still some interesting observations.

7.1. Reflections

We did not observe much VR sickness in participants, the results from the SSQ were not surprising. Our evaluation procedure was very simple and not sickness inducing, so it is not surprising that there were no significantly differing results between the groups. Only a single participant got mild sickness in one of the SSQ categories.

After comparing the focus values between the groups we ended up with a result which we were expecting. The participants of the experimental group got significantly better results when it came to keeping higher focus. This points toward the theory that the experimental group needed to stay focused according to our method of measuring focus. However, the control group was able to perform the tasks without needing to focus since the randomization did the work for them.

One of the other evaluation measurements was timing the completion of different tasks. The results from the playroom should not be considered important. Recording data in the playroom was not originally planned. Therefore, there was no strict protocol for that part of the evaluation. This caused some differences in the time spent in the playroom between the test locations. However, there was a statistically significant difference between the groups in the completion times of timed teleportation task. Originally, it was planned to investigate if being under pressure would cause decreased focus values. It was not expected that the experimental group was able to complete the time limited task in significantly lower amount of time. We believe that this was due to the groups learning the course of the game from the previous task. Both groups had this advantage, but the experimental group also might have learned to use the teleportation feature better, while the control group was limited to the same random generator. This might point to an observation that the experimental group learnt to use our focus measuring method quicker.

Some unexpected bugs were encountered during the puzzle task. These bugs caused several outliers in that particular task. This heavily affected the outcome due to our limited pool of participants. One of our participants had a physics object launch itself away. This was caused by an object controlled with telekinesis being released while its collision model was clipping with the environment. Another participant trapped a physics object behind a stand it was supposed to be placed and had some trouble interacting with it afterwards. Both participants were able to finish the task, but with delayed completion times.

There are not many certain conclusions to be made from the results of the Post-Questionnaire due to none of the data points being statistically significant. However, the Teleportation category was almost significant with a p-value of 0.071. Here can be noted that the control group generally rated the questions regarding the teleportation higher than the experimental group. This is interesting, since the experimental group was able to perform the timed teleportation task faster.

Both groups thought the features were entertaining. During the interviews, most of the participants believed that the features were interesting and saw the potential of utilizing BCI devices to enhance virtual interaction. Some participants noticed that blinking works as a good method of releasing objects from telekinesis, which we also noticed during implementation. This might point towards certain muscle signals being good methods for controlling objects in a virtual environment.

7.2. In Relation to Other Works and Findings

Cattan et al. put forward recommendations for integrating P300-based BCI into video games [30]. They determined that slow-paced adventure and puzzle games were a well-suited application for BCI if the user is given enough time for each action. Arguably our Teleportation and Puzzle rooms were miniature versions of each mentioned category. In the same paper, it was deemed that BCI devices were not optimal for applications where the user is moving a lot as this causes artifacts to the signal. However, Teleportation was said to be a worthy adaptation of BCI, since the technique requires no movement that would lower the overall quality of the EEG signal. A similar focus-based method of teleportation was proposed. The main difference was that the decision to teleport was confirmed by pressing a button on the joystick [30]. They hypothesized that even though no motion was visible to the user, the sudden cut from one place to another could induce motion sickness in the user [30]. When looking at our results, there are no noticeable signs of such a phenomenon.

An interesting prototype for Telekinesis could be created if our framework and elements of creation by Jedi ForceExtention [20] would be combined. Jedi ForceExtention allows users to move and rotate virtual objects by using a controller and head tilting. Both projects would complement each other nicely as they would be able to cover each other's shortcomings. Our implementation did not allow any rotation or pulling of the objects. Our project did not use a controller either. Jedi ForceExtention received complaints that the interaction state was not conveyed clearly enough [20]. Participants felt that feedback, such as a glow or a color around the object, would fix this problem. This feature is implemented in our project in the form of a color change.

7.3. Limitations

Many factors have an effect on the results, which we have to take into consideration. A clear factor is a limited pool due to Covid-19 and, therefore, a small number of participants (n= 13). This decreases p-values which leads to most of the results not being statistically significant. Also, these participants were acquaintances of the authors which might introduce an element of bias towards the study.

There were small differences between the study locations. The studies were performed in 3 different semi-controlled locations with 3 different computer systems. We mitigated this factor by using a consistent protocol for every test. The models of the Muse 2 and the VR headset were the same, but they were different units. The differences caused problems especially with the Bluetooth connection of Muse 2. The connection had varying levels of reception and this caused some data loss. We had one occasion where the Bluetooth connection crashed during the test due to a bad connection.

The Bluetooth transceiver is located on the side of Muse 2. The spatial position of the Muse 2 had an effect on the Bluetooth connection. We noticed that the connection got worse when there were obstacles between the Muse 2 and the Bluetooth adapter. This meant that when the test participant was looking at a certain position, the connection could start to lag considerably. The normal frequency for samples sent by BlueMuse was 250hz. When problems arose, the frequency could drop all the way down to 30hz, before the connection would drop out. We noticed that we could reduce the probability of the lag by relocating the Bluetooth adapter to a more elevated position. The majority of the time, the connection suffered no lag though.

In addition, the connection had a varying amount of noise. The amount of noise was heavily dependent on the participant for unknown reasons. For some people, there were no problems at all and Muse 2 started working almost instantly. Unfortunately, we did not manage to get a perfect signal for some, even after trying to adjust the placement of the Muse for several minutes. Therefore, for some people, we had to do the test with more noisy signals, which lowers the focus value. This might also influence the focus value differences between the test groups.

There exist different algorithms to determine focus from EEG signals. Our calculations are based on standard deviations, which might not be a perfectly accurate representation of the volume of focus. Another option would have been to use Fast Fourier transform (FFT). This changes the signal from time- to frequency dimension. The different frequency bands from the EEG gets revealed. Different states of the brain can be seen in the frequency bands [31]. By using these bands we could study which band(s) we could use to determine the volume of focus more accurately. On the other hand, our algorithm is appealing because of its simplicity and quickness, which could be more suitable for real-time EEG analysis in interactive media.

The amplitude of the raw EEG from Muse 2 is mainly controlled by muscle movement. We noticed this quite quickly since blinking had instantly a significant effect on the graph. Also, eye and body movement was seen in the EEG easily. It can be argued that muscle and eye movement play a major role in focus. However, if the user knows that the focus values are based on mainly muscle movement, he could partially "fake" the state of concentration.

Another technical choice was made with the randomization algorithm for the test group. Designing the randomization was a complex question. The main question was how should the randomization be designed so that the results would be completely unbiased. It is very difficult to find the precise solution for this, therefore the question has to be broken into different elements. The generated values should not be too harsh, nor too forgiving. It might be ideal that the tasks during the evaluation test would be equally difficult for both test groups. In our implementation, the generated values had a guaranteed chance of succeeding in the task provided that the user is looking at the object. This way, navigating through the course would not be too difficult. However, this raises questions of the limit of it being too easy. The fluctuation of the values is another aspect that has an effect on the "realism" of how the focus should behave. The color transformation was also different for the control group in the telekinesis rooms since the generated values do not change the color smoothly as seen in fig. 15.

There are also several other aspects which have an effect on the results. The background differences between the test groups might increase the fluctuation of the opinions and completion times. Most of the differences were in VR and video game experience and in gender distribution. The instruction is given to the participant before the test could have been more detailed too.

After the test, we noticed that the participants learned the layout of the teleportation room very quickly. When completing the teleportation task without the time limit, the participant had to figure out the layout of the teleportation nodes. This leads to time spent looking around the environment to find the next node to teleport to. However, after the task was done without the time limit, the participant had to complete the same room again with a time limit as described in fig. 13. Therefore, the placement of the nodes was already familiar to the participant. This undesired factor possibly explains why the completion time decreases in time teleportation as seen in the table. 5.

7.4. Future Work

The conditions of our study caused some limitations on the observations. Further testing should be done with a larger sample size of participants. The testing conditions should also be more standardized to reduce some of the variables we encountered. Connectivity should be given greater scrutiny with better setups and receivers.

In our study, the main focus was to create an interface between a virtual environment and Muse 2 BCI. The main focus was not to design a precise algorithm to calculate the volume of focus. The algorithm and method for measuring the focus could be improved upon. The calculation of focus value could possibly be made more accurate by using more complex algorithms like using FFT. In future studies, these kinds of concepts could possibly be used to determine the value of focus without taking into account muscle movement. However, it is possible that using the typical methods of measuring focus would not be suitable for video games. For instance, it is possible that this kind of focus estimation would be too unresponsive to be used in video games.

Hardware improvements could be made in future studies. Using a more intricate BCI device could reduce the problems we encountered. Muse 2 had a rather limited array of data with only 4 different EEG sensors. Having more data points with higher accuracy could enable the creation of more complex algorithms for analyzing the collected data. One other problem in our hardware was the compatibility of using the BCI and HMD at the same time. Some kind of BCI integrated into an HMD could prove a valuable asset for further study on the subject. This would improve comfort for the user, and possibly reduce the noise from HMD. An integrated solution could also help with the connection problems we encountered. If the BCI and HMD used the same established connection to the computer, connectivity problems would be reduced.

8. CONCLUSIONS

In this study, we experimented with the usage of EEG biosensors within a VR environment. We designed the virtual environment by using Unity game engine. For the EEG sensors, we used a headband called Muse 2. The environment consisted of simple game objects like cubes and spheres since it was the minimal design for this study to be conducted. There were two different methods of interaction we experimented with; telekinesis and teleportation. In telekinesis, the user was able to control an object by looking at it and focusing enough. By maintaining good focus and by moving one's head, the user was able to move the object within the environment. If the focus dropped too low, the grip from the object was lost. For teleportation, the user had to look at a teleportation node with a good focus for a certain amount of time. After that, the user could teleport to the coordination of the corresponding node.

The virtual objects in the environment changed color based on the calculated focus values of the user. The color spectrum we used was from red to green, red being the least focused. For telekinesis, the color of the objects represented the focus value directly. However, in teleportation, the color of the object was based on the elapsed time of having a high enough focus value. The calculation of the focus value was implemented by us.

The calculation for determining the focus value from the raw EEG was done with simple methods since the accuracy of the algorithms was not our main focus. Designing the perfect algorithm to determine focus values in real-time would require an another study. The algorithm used in this study was based on the standard deviation of the amplitudes of the EEG. The standard deviations were converted to a more workable scale by using the help of the function which is plotted in fig. 10. The color of the objects was determined by the values from that scale. Since the system framework is now ready, it is easy to further tweak and improve multiple aspects of the implementation.

Due to Covid-19, we had quite a small sample size which influences the generalizability of our results. However, we were successful in creating a working interface between BCI and the virtual environment. For the evaluation, we defined two test groups. In the evaluation, we gathered some interesting observations which indicate that our implementation was somewhat successful and open to further research. This includes opinions on the entertainment value of the interactive features and the focus value differences between the test groups as presented in table 4.

For certain, the utilization of EEG sensors has a lot of potential for use cases to be discovered in the entertainment industry. It seems intriguing to us that in the future biosensors could be integrated into a VR headset. The sensor data could be processed in real-time to gain additional information about the state of the user. The data could be used for in-game interaction for example moving objects around. This would create a unique game experience where an additional element of user input is provided. The evolution of the VR experience is far from over.

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10. APPENDICES

Pre-Questionnaire

1. What is your subject number?

____

Informed consent

You are participating in a study assessing different interaction methods in VR. We collect pseudonymized data that includes:

-Pre- and Post- experiment questionnaires and all their contents

-Digital data from the experiment (EEG data, digital statistics)

-Possibly audio and photography during and after the experiment (You can indicate separately if you wish the audio not to be recorded or no photos taken. If you consent to the collection of audio, the data is pseudonymized by transcribing into text format and the original audio files will be destroyed. The text transcript will only contain test relevant material, no personal blurs or comments are transcribed.)

All the collected data will be anonymous or pseudonymized. The analysis results are published in thesis, scientific reports, and papers. By answering and submitting this questionnaire you consent to participating in the experiment and data collection. You are allowed to withdraw your consent at any time during this experiment.

We appreciate fully honest answers.

2. I have understood the information above and agree with the above terms

Mark only one oval.

- Yes
- No

3. I understand my participation is voluntary and that I'm free to withdrawn at any time

Mark only one oval.

- Yes
- No

4. What is your sex?

Mark only one oval.

- Man
- Woman
- Other

5. How old are you?

____

6. How experienced are you with VR

Mark only one oval.

	1	2	3	4	5	
Never used VR before						I use VR regularly

7. How often do you play video games?

Mark only one oval.

	1	2	3	4	5	
Never play video games						I play video games daily

8. Do you get carsick or seasick easily?

Mark only one oval.

	1	2	3	4	5	
Never						Very regularly

9. Have you ever used meditation assist tools before?

Mark only one oval.

- Yes
- No

10. Are you color blind in any way?

Mark only one oval.

- Yes
- No

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Post-Questionnaire

You can answer with English or Finnish

1. What is your subject number?

____

Simulator Sickness Questionnaire

2. Circle how much each symptom below was affecting you during the VR experience

Mark only one oval per row.

	None	Slight	Moderate	Severe
General discomfort	◯	◯	◯	◯
Fatigue	◯	◯	◯	◯
Headache	◯	◯	◯	◯
Eye strain	◯	◯	◯	◯
Difficulty focusing	◯	◯	◯	◯
Salivation increasing	◯	◯	◯	◯
Sweating	◯	◯	◯	◯
Nausea	◯	◯	◯	◯
Difficulty concentrating	◯	◯	◯	◯
Fullness of the head	◯	◯	◯	◯
Blurred vision	◯	◯	◯	◯
Dizziness with eyes open	◯	◯	◯	◯
Dizziness with eyes closed	◯	◯	◯	◯
Vertigo	◯	◯	◯	◯
Stomach awarness	◯	◯	◯	◯
Burping	◯	◯	◯	◯

Telekinesis (Puzzle room)

3. I was able to interact with the environment the way I wanted to.

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Perfectly

4. The color of the objects represented my concentration accurately in the puzzle room

Mark only one oval.

	1	2	3	4	5	6	7	
No correlation at all	◯	◯	◯	◯	◯	◯	◯	Perfectly

5. The puzzle task was (1 difficult, 7 easy) to perform

Mark only one oval.

	1	2	3	4	5	6	7	
difficult	◯	◯	◯	◯	◯	◯	◯	easy

6. If it was difficult, what did you struggle with?

____

____

____

____

____

7. Did you gain enough feedback for your actions in puzzle room?

Mark only one oval.

	1	2	3	4	5	6	7	
Not enough	◯	◯	◯	◯	◯	◯	◯	Fully enough

8. It was easy for me to maintain focus while controlling objects

Mark only one oval.

	1	2	3	4	5	6	7	
Very difficult	◯	◯	◯	◯	◯	◯	◯	Easy

9. I used a particular method to release objects from telekinesis

____

____

____

____

____

Teleportation

10. I was able to interact with the environment the way I wanted to.

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Perfectly

11. The teleportation task was (1 difficult, 7 easy) to perform

Mark only one oval.

	1	2	3	4	5	6	7	
difficult	◯	◯	◯	◯	◯	◯	◯	easy

12. The color of the objects reflected my level of concentration accurately in the teleportation room

Mark only one oval.

	1	2	3	4	5	6	7	
No correlation	◯	◯	◯	◯	◯	◯	◯	Perfectly

13. Did you gain enough feedback for your actions in teleportation room?

Mark only one oval.

	1	2	3	4	5	6	7	
Not enough	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Fully enough

14. I felt the time limit effected my performance in the teleportation room

Mark only one oval.

	1	2	3	4	5	6	7	
It made my performance worse	⬭	⬭	⬭	⬭	⬭	⬭	⬭	It made my performance better

General questions

15. How was the length of the test?

Mark only one oval.

	1	2	3	4	5	6	7	
Too short	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Too long

16. Did you find teleportation and telekinesis entertaining?

Mark only one oval.

	1	2	3	4	5	6	7	
Not fun at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Very entertaining

17. Which features did you enjoy?

Tick all that apply.

- ☐ Telekinesis
- ☐ Teleportation

18. If features from this projects were implemented in games, could you see yourself using them?

Mark only one oval.

- Yes
- No
- No Opinion

19. Did you find it comfortable to wear both Muse 2 and VR headset at the same time?

Mark only one oval.

	1	2	3	4	5	6	7	
Very uncomfortable								Very comfortable

20. Could you see similar brain signal controlled features implemented into applications or videogames in the future?

Mark only one oval.

- Yes
- No
- No Opinion

21. Did you experience any fatigue during any part of the test?

Mark only one oval.

- Yes
- No

22. Can you come up with any other use cases for brain wave sensors in video games?

23. Any other feedback?

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